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Reverse sea to predict flanking transmission in timber framed constructions

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Abstract

Prediction of Flanking Transmission for lightweight constructions is a sensitive procedure. Lightweight structures are anisotropic and are composed of multiple possibilities of build-ups and structural junctions. The article presents an example of structure composed of Cross Laminated Timber. The modelling strategy to predict such structures is detailed. The framework of the methodology is Statistical Energy Analysis (SEA). SEA involves cutting the structure into subsystems and decomposing the spectrum into third-octaves or octaves. In this way, the exchange of energy flow in the substructures can be analysed. The parameters that govern vibrational transmission between subsystems are damping and coupling loss factors and can be identified experimentally by reversing the problem. The approach is, first, based on sub-structuring strategy of structure; second, on experimentally measured coupling and damping loss factors; third, on extracting vibration level difference to estimate one by one all flanking passes.

Keywords: Timber Building, Flanking Transmission, SEA, Reverse SEA, Vibro-acoustics

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1 Introduction

The more common model to predict flanking transmissions is based on Statistical Energy Analysis (SEA), it has been elaborated for monolithic concrete walls forming a 'T' or a cross junction: EN 12354, [1], [2], [3]. In the standardized model each sub-system represents a wall. It has been shown that this model is accurate for heavy, homogenous and low dumped structure such as concrete. The simplified theory can't be applied for lightweight timber construction where walls are composed of double leaf ribbed panels and the junction composed of inhomogeneous assembly. A modified model was proposed to overcome this complexity. All about this topic is discussed in the ongoing "Silent Timber Build" project.

In this article, we present a methodology using Reverse SEA with no simplification, where all parts of the construction is represented in the model. Threw a progressive procedure, based on measurement, we build a hybrid prediction model composed of both experimental approach and on expertise.

Our experimental approach was performed on Cross Laminated Timber (CLT). This was guided by the expansion market for this type of building systems. Today, CLT is more and more used, it opened a new capacity for wood to be used for multi-storey buildings.

2 Flanking transmission prediction

Flanking transmission is known to be responsible of 50% of acoustic insulation. This matter has often been studied and several calculation approaches are available in the literature. The more common model is based on a simplified SEA application.

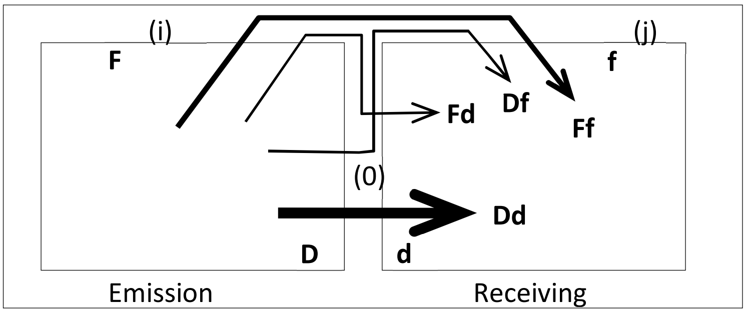


Figure 1 : Conventional designation of direct and flanking transmissions

For homogeneous walls perfectly assembled a T junction creates a SEA model of 5 sub-systems: 2 cavities (rooms) and 3 walls forming the junction. Each path corresponds to a noise reduction:

$$\tau_{ij}=\sqrt{\left(\tau_i\tau_j d_{ij} d_{ji}\frac{S_j S_i}{S_0^2}\right)} \tag{1}$$

With R = 10 Log (1/τ) :

$$R_{ij}=\frac{R_i}{2}+\frac{R_j}{2}+\frac{D_{ij}+D_{ji}}{2}+10\log\frac{S_0}{\sqrt{S_i S_j}} \tag{2}$$

In case of light weight constructions the vibration transmission via double walls, the model used must be different. In year 2000 EN12354 was published, the calculation model uses:
R, Sound transmission loss of wall and floors,
T_s, Structural reverberation time,
K_{ij}, Vibration reduction index.

K_{ij} is specific to junction type. It is for homogeneous heavy weight structures

$$K_{ij}=\frac{D_{ij}+D_{ji}}{2}+10\mathrm{Log}\frac{l_{ij}}{\sqrt{a_i a_j}} \tag{3}$$

With ai equivalent absorption length:

$$a_i=\frac{2.2\pi^2 S_i}{c_0 T_s}\sqrt{\frac{f_{ref}}{f}} \tag{4}$$

For lightweight walls and floors strongly damped the method proposes Kij formulas:

$$K''_{ij}=\frac{D_{ij}+D_{ji}}{2}+10\mathrm{Log}\frac{l_{ij} l_0}{\sqrt{S_i S_j}} \tag{5}$$

And

$$R_{ij}=\frac{R_i}{2}+\frac{R_j}{2}+K''_{ij}+10\log\frac{S_0}{l_{ij} l_0} \tag{6}$$

In 2007 a COST action FP0702 was started, Working group 1 on modelling, proposed a more appropriated prediction method for timer framed construction. The group acknowledged any other calculation method using FEM, SEA, Reverse SEA or Virtual SEA. This opened several research axes and created a new generation of projects like Silent Timber Build.

$D_{v,ij}$ (vibration reduction level) is measured in situ on junctions. The measurement method is based on a uniform mechanical excitation using several hammer or shaker positions. $D_{v,ij}$ are measured using 12 transducers positions.

The sound transmission loss resulting of all passes is calculated with:

$$R' = -10\log\left[10^{-\frac{R}{10}} + \sum_{ij} 10^{-\frac{R_{ij}}{10}}\right] \tag{7}$$

And finally, the sound reduction is obtained with R':

$$D_{nT} = R' - 10\log\frac{0.16\ V}{T_0 S_s} \tag{8}$$

In the following, we present SEA for direct prediction and Reverse SEA for characteristics determination.

3 SEA theory for lightweight building prediction

Statistical Energy Analysis theory involves subdividing the structure into subsystems and decomposing the frequency spectrum into third-octaves or octaves. In this way, the exchange of energy flow in the substructures can be analysed. The parameters that set power flow vibrational transmission between subsystems are damping and coupling loss factors and can be identified experimentally by reversing the direct SEA problem as exposed in next paragraphs.

Using Direct SEA, the modeling starts by decomposing the system into a set of components (the subsystems). For each of them the dynamical behavior is then predicted by SEA. Each subsystem is classically defined by:

- a modal density, N, that represents the statistical local resonances of the subsystem,
- a damping loss factor, η or DLF, which represents the fraction of power lost in steady-state.

The exchange of vibrational power between two coupled subsystems i and j is described by a pair of coupling loss factors (η_{ij} and η_{ji} or CLF) related by a reciprocity relationship:

$$\eta_{ij} N_i = \eta_{ji} N_j \tag{9}$$

The total vibrational energy of a subsystem can be obtained from its spaced and frequency averaged velocity v^2 (the measurable engineering quantity and its total mass m) by the relationship:

$$E = mv^2 \tag{10}$$

E represents the total energy stored in resonant modes in a given frequency band of analysis which will be assumed to be centered around a radian frequency ω and acoustic pressure is related to velocity in cavities by

$$p = \rho c \cdot v \tag{11}$$

In this band, SEA states that the exchange of power between coupled subsystems can be expressed as

$$P_{ij} = \omega\left[\eta_{ij} N_i \varepsilon_i - \eta_{ji} N_j \varepsilon_j\right] = \omega N_i N_j \beta_i^j \left[\varepsilon_i - \varepsilon_j\right] \tag{12}$$

Where β_i^j is the mean modal coupling loss factor between one pair of local modes of subsystems i and j and ε_i the mean modal energy. From this, $\eta_{ij} = \beta_{ij} N_j$

Knowing all modal densities, DLF and CLF, it is possible to predict the energy state of the fully coupled system excited by external forces by writing a set of energy balanced equations traducing the energy conservation in each subsystem:

$$\frac{P_i}{\omega} = \eta_i E_i + \sum_{\text{j}}^{\text{All j coupled to i}} \left\{\eta_{ij} E_i - \eta_{ij} E_j\right\} \tag{13}$$

where P_i is the power delivered in subsystem i by its applied external forces.

This theory: “**Direct SEA**” is used to predict energy flow between subsystems. The energy is converted into pressure level for cavities or rooms and into vibration level for flexural plates.

To predict flanking transmission one will have to safely substructure the building system and then introduce the accurate DLF and CLF of flexural plates and junctions. Below, we show how DLF and CLF can be determined by testing the structure using **Reverse SEA**.

4 Reverse SEA used to determine CLF and DLF

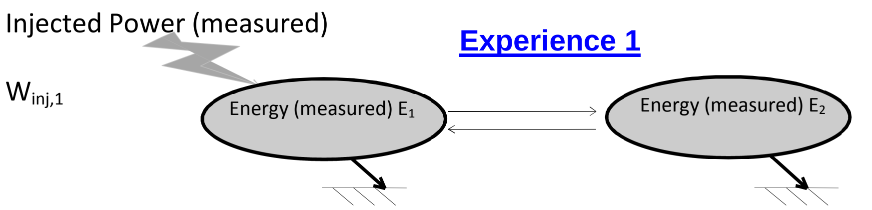
When the structure is cut into substructures it is possible to measure dumping and coupling loss factors corresponding to the physical studied structure, this theory is called “Reverse SEA”. The methodology is well known but not currently used, the testing is time consuming when one is not using a Reverse SEA software. For our testing approach we used Experimental SEA developed by InterAC Toulouse.

To determine [η] DLF and CLF matrix energy and power injected are measured.

4.1 Experimental methodology

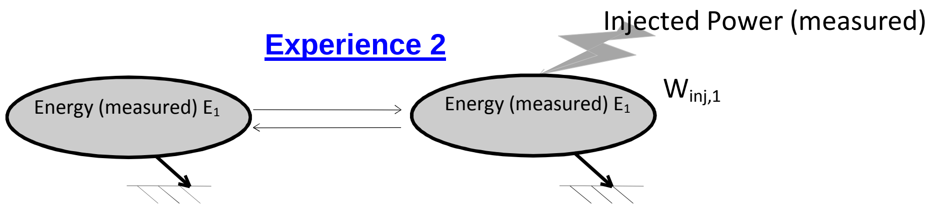
(1) Power is injected sequence by sequence in each subsystem of the structure
(2) Equilibrium of each configuration – power injected – is written
(3) n equations are derived,

Below we show the methodology for two subsystems:



Experience 1: Power injected in Subsystem 1

$$\begin{bmatrix} -\eta_1{}^* & \eta_{21} \\ \eta_{12} & -\eta_2{}^* \end{bmatrix} \begin{pmatrix} E_{11} \\ E_{21} \end{pmatrix} = \begin{Bmatrix} \dfrac{-W_{inj,1}}{\omega_0} \\ 0 \end{Bmatrix}$$



Experience 2: Power injected in Subsystem 2

$$\begin{bmatrix} -\eta_1{}^* & \eta_{21} \\ \eta_{12} & -\eta_2{}^* \end{bmatrix} \begin{pmatrix} E_{12} \\ E_{22} \end{pmatrix} = \begin{Bmatrix} 0 \\ \dfrac{-W_{inj,2}}{\omega_0} \end{Bmatrix}$$

Figure 2 : Experimental methodology for Reverse SEA

Both equations can be written as follow:

$$\begin{bmatrix} -\eta_1{}^* & \eta_{21} \\ \eta_{12} & -\eta_2{}^* \end{bmatrix} \begin{pmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{pmatrix} = \begin{Bmatrix} \dfrac{-W_{inj,1}}{\omega_0} & 0 \\ 0 & \dfrac{-W_{inj,2}}{\omega_0} \end{Bmatrix} \tag{14}$$

Then the [ηij] matrix coefficient determination is done:

$$\begin{bmatrix} -\eta_1{}^* & \eta_{21} \\ \eta_{12} & -\eta_2{}^* \end{bmatrix} = \begin{Bmatrix} \dfrac{-W_{inj,1}}{\omega_0} & 0 \\ 0 & \dfrac{-W_{inj,2}}{\omega_0} \end{Bmatrix} \begin{pmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{pmatrix}^{-1} \tag{15}$$

For n subsystems:

$$\begin{bmatrix} -\eta_1^* & \eta_{21} & . & . & \eta_{n1} \\ \eta_{12} & -\eta_2^* & & & . \\ . & & . & & . \\ . & & & . & . \\ \eta_{1n} & . & . & . & -\eta_n^* \end{bmatrix} = \begin{Bmatrix} \frac{-W_{inj,1}}{\omega_0} & 0 & & 0 \\ 0 & \frac{-W_{inj,2}}{\omega_0} & & 0 \\ & & . & 0 \\ 0 & 0 & 0 & \frac{-W_{inj,n}}{\omega_0} \end{Bmatrix} \begin{pmatrix} E_{11} & E_{12} & . & E_{1n} \\ E_{21} & E_{22} & . & \\ . & & . & \\ E_{n1} & & & E_{nn} \end{pmatrix}^{-1} \qquad (16)$$

We conducted this testing methodology for different types of building systems: double leaf timber framed wall, I beam framed floors, T junction of 3 framed walls and a cross junction between 4 apartments composed of 2 walls and 2 floors.

a) T junction (horizontal) composed of 3 double leaf timber framed wall,

b) Cross junction (vertical) composed of 2 walls and 2 floors

c) T junction (vertical) composed of 2 facades walls and 1 floor.

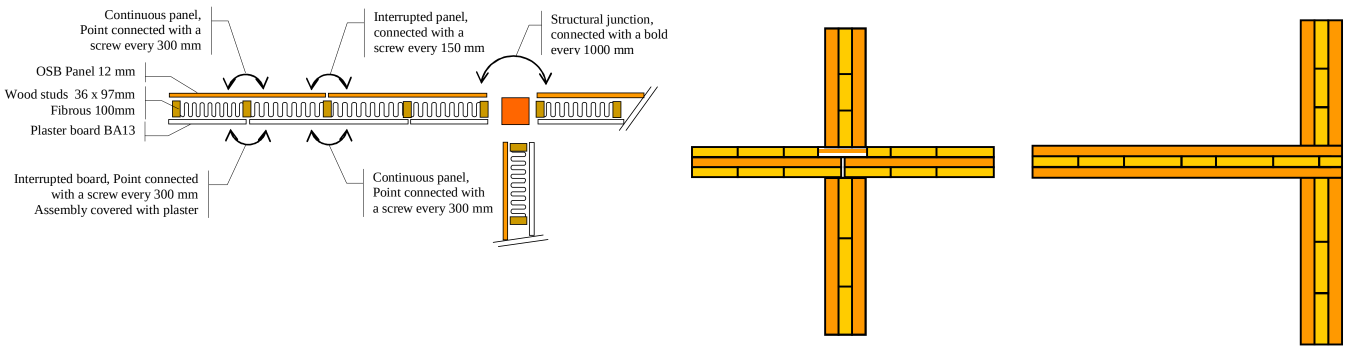


Figure 3 : Example of 3 tested building systems

5 Measurement of coupling and damping on a CLT building

For the characterisation campaign, we were invited to measure in-situ characteristics on different buildings of Woodeum / PROMICEA. We planned to proceed at different stages of structural implementation. First stage was in February 2016, in Ris-Orangis, France. The measurement was made on the structure without lining. The campaign took place during night for quiet need reasons.

The structure is composed of Cross Laminated Timber (CLT) thick panels for walls and floors structural constitutions, Figure 3 b) and c).

Figure 4 : Tested building systems, CLT walls and floors

For testing, we used Exp-SEA® software developed by InterAC. The tool is very convenient to use, Reverse SEA generates hundreds of files. Each hammer shock is recorded with all acceleration.

First step, is to measure the mobility for power injected calculation. Second step, is to measure transfers between subsystems.

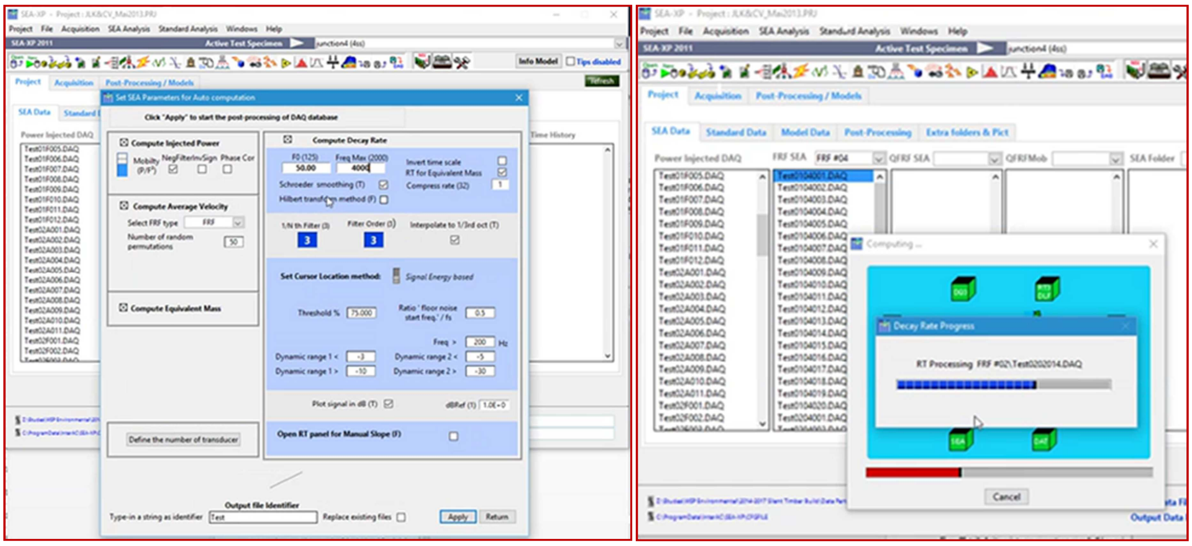


Figure 5 : Processing from data acquisition to reverse SEA

The software guide the team during the measurement and then it manages all files recorded to extract CLF and DLF. Each junction testing takes 2 hours for measurement (preparation and acquisition).

From data acquisition on the 4 subsystems, the tool is automatic, it reverses the Energy matrix * Power injected resulting on DLF and CLF matrix.

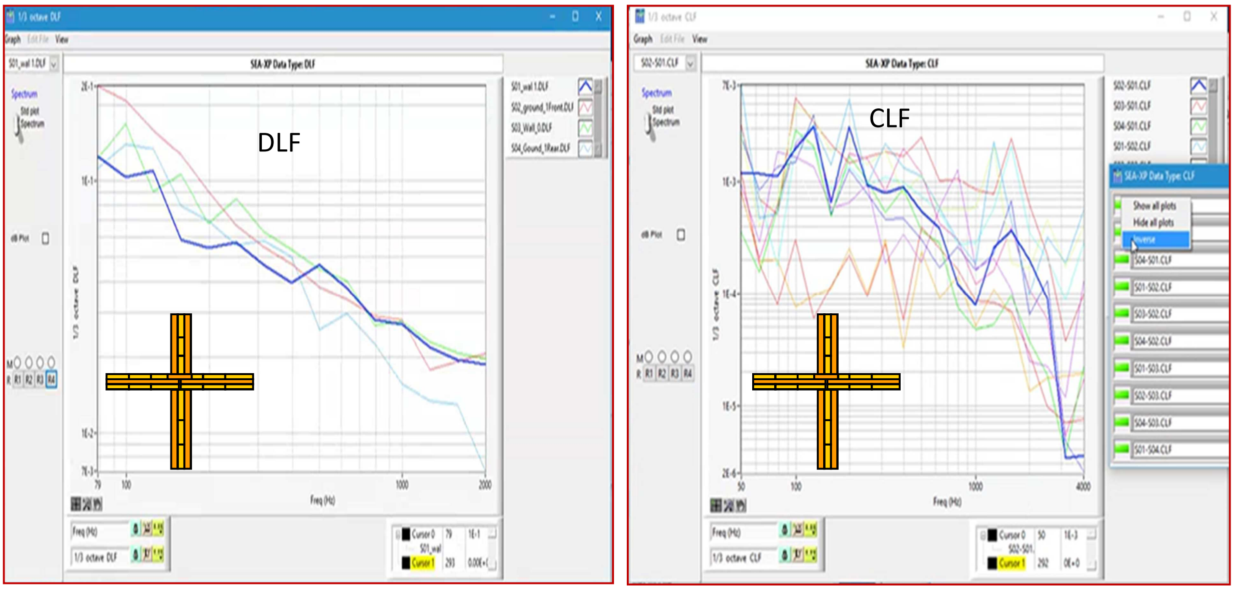


Figure 6 : DLF and CLF measured on a CLT cross junction of 2 walls and 2 floors

As described before the experimental procedure end up with CLF and DLF that can be implemented in a model for flanking passes calculations. The model composed from deterministic and measured couplings is dedicated only for vibration energy flow analysis. For acoustical use we add to the model acoustical cavities to represent emission and receiving rooms as well as cavities between panels in double wall. With this model it is possible to calculate the different sound transmission losses R_{ij} direct or flanking.

6 Conclusions

The prediction method, using SEA for evaluation the flanking transmissions of wood based structures (wall and floors) has been presented and will be further investigated within the “Silent Timber Build” project. SEA is the theory framework for homogeneous construction. When one consider more complex constructions such as lightweight timber framed structures the simplified SEA theory is useless. We propose an original methodology using subsystem identification and reverse SEA to model a typical junction.

Reverse SEA method opens up interesting perspectives for acoustic engineering and its results are directly appropriate for the construction industry. All the modeling expertise, characteristics, CLF and DLF database, are being implemented in SEA-Wood model, where typical cases for building modeling are studied within the Silent timber Build Project.

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References

[1] CEN, European Standard EN 12354-1 Building acoustics - Estimation of acoustic performance of buildings from the performance of products. Part 1 : Airborne sound insulation between rooms. Editions de l'AFNOR, 1999, 57 pages.

[2] Gerretsen, E. Calculation of the sound transmission between dwellings by partitions and flanking structures. Applied acoustics, 1979, Vol 12, pp. 413-433.

[3] Gerretsen, E. European development in prediction models for building acoustics. Acta Acoustica June 1994, Vol 2, pp. 205-214.

[4] SEA-XP® software for vibration and vibro-acoustic experimentations, developed by Gérard Borello, InterAc, France. Special SEA-XP packaged for wood construction tests.

[5] G. Borello, L. Gagliardini. Virtual SEA : towards an industrial process. 2007-0123-02 SAE NVC (Noise and Vibration Conference) Proceedings May 15-17, 2007 St. Charles, Illinois, USA.

[6] Bosmans I. Analytical modelling of structure-borne sound transmission and modal interaction at complex plate junctions. Thèse de l'Université Catholique de Louvin, rapport UDC 534, 8 mai 1998, 246 pages.

[7] Kouyoumji J.L. Caractérisation des parois courantes et des liaisons structurales pour la prévision de l'isolement acoustique d'une construction en bois, thèse de l'Université de Savoie LGCH-ESIGEC, soutenue le 15 décembre 2000, 185 pp.

[8] Kouyoumji J.L., Sub-structuring of timber construction and prediction of flanking transmission using SEA and reverse SEA. 35th Internoise, 3-6 december 2006, Honolulu, Hawaii, USA